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Increasing the Wear Resistance of Stamping Tools for Coordinate Punching of Sheet Steel Using CrAlSiN and DLC:Si Coatings

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Abstract: The punching of holes or recesses on computer numerical control coordinate presses occurs in sheets at high speeds (up to 1200 strokes/min) with an accuracy of ~0.05 mm. One of the most effective approaches to the wear rate reduction of stamping tools is the use of solid lubricants, such as wear-resistant coatings, where the bulk properties of the tool are combined with high microhardness and lubricating ability to eliminate waste disposal and remove oil contaminants from liquid lubricants. This work describes the efficiency of complex CrAlSiN/DLC:Si coatings deposited using a hybrid unit combining physical vapor deposition and plasma-assisted chemical vapor deposition technologies to increase the wear resistance of a punch tool made of X165CrMoV12 die steel during coordinate punching of 4.0 mm thick 41Cr4 carbon structural steel sheets. The antifriction layer of DLC:Si allows for minimizing the wear under thermal exposure of 200 °C. The wear criterion of the lateral surface was 250 µm. The tribological tests allow us to consider the CrAlSiN/DLC:Si coatings as effective in increasing the wear resistance of stamping tools (21,000 strokes for the uncoated tool and 48,000 strokes for the coated one) when solving a wide range of technological problems in sheet stamping of structural steels.

Keywords: coating; die; DLC; nitride layer; PACVD; PVD; punch; tribological test; X165CrMoV12; wear resistance

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1. Introduction

Sheet metal stamping technologies are among the most common pressure processes for producing blanks and finished parts in mechanical engineering. Cold stamping separation operations such as cutting, punching, etc., are implemented in stamping tools consisting of a movable punch and a fixed die, in which the product is formed as a result of the pulsed force action of the punch and the breaking of the bonds of the crystal lattice of the sheet material, ensuring high productivity and accuracy of stamped products at a relatively low cost [1,2].

When processing on computer numerical control (CNC) coordinate punching presses, which are widely used in the industrial manufacturing of products made of aluminum alloys and stainless and carbon structural steels, the coordinates are determined according to a given software algorithm, where through punching of holes or recesses occurs in the sheet material at high speeds (up to 1200 strokes per minute) and with high processing accuracy (error of no more than 0.05 mm). Using coordinate punching, holes and recesses of various configurations are formed (Figure 1), and a wide range of serial and mass products is manufactured, such as the housings of lighting devices, electronic equipment and devices for transmitting electromagnetic energy, elements of ventilation and air conditioning systems, vehicle parts, etc.

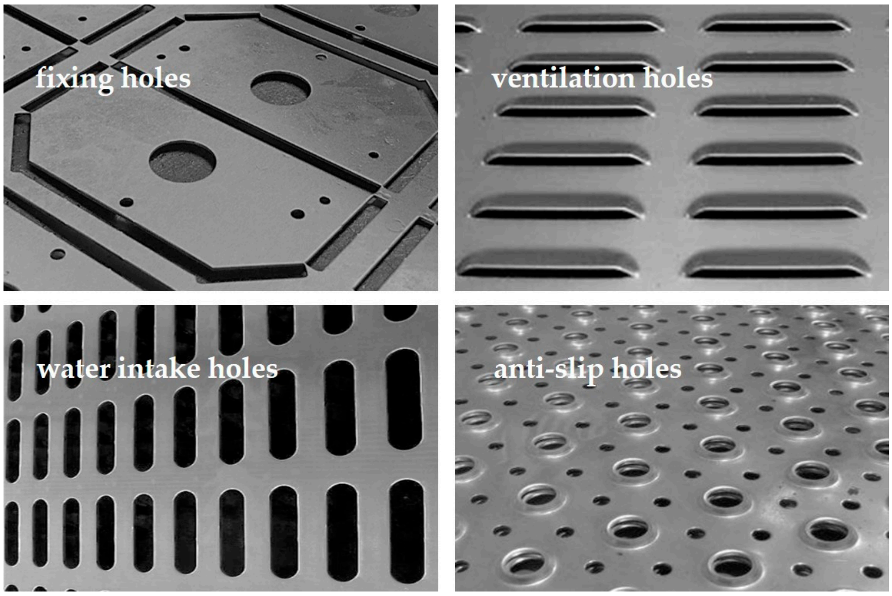


Figure 1. Some typical hole patterns in sheet metal products produced on CNC punching machines.

Coordinate punching presses are characterized by high efficiency, and there is no thermal impact on the sheet material during processing, which ensures energy savings and eliminates the possibility of metal deformation resulting from overheating. Therefore, despite the development of alternative technologies (laser and plasma cutting, electrical discharge machining, etc.) for processing structural steels and alloys, the separation operations of cold sheet stamping today still remain the most accessible and common for solving a wide range of technological problems [3,4].

Currently, the most common materials for manufacturing tools for cold sheet stamping separating operations are X82WMoCrV6-5-4 high-speed tool steel and X165CrMoV12 tool die (or mold) steel (according to the DIN standard). The critical importance of ensuring the high efficiency of the processing products on coordinate punching presses is the wear resistance of the stamping tools, which largely depends on the properties of its surface layer, such as the microhardness of the working surfaces, the intensity of adhesion to the material under processing, etc. During operation, the working surfaces of the separating punch and die are subjected to impact loading, high contact pressures, and tangential stresses due to friction between the tool's and the workpiece's surfaces. In this case, the punch takes the greatest loads, and the violation of its working condition due to various types of wear occurs earlier than for the die [5,6]. The loss of the working capacity of the stamping tool occurs as a result of various phenomena, such as the adhesion and abrasive wear of the working surfaces, the appearance of burrs, and the formation of build-ups due to the capture and transfer of particles of the material under processing (the prevalence of the wear mechanism primarily depends on the material under processing and the thickness of the workpiece). These processes lead to a change in the gap between the punch and die, an increase in the stamping force, deviations in the shape and size of the punched holes and cut-out parts, an increase in the roughness of the cut surface, and the appearance of burrs, requiring the immediate replacement of the tool to prevent defects in the stamped products [7,8].

Lubricants are used to reduce stamping forces, minimize the intensity of adhesive adhesion of the tool material to the workpiece and wear of the stamping tool, and ensure the high quality of the products during sheet metal stamping. The most significant effect of the lubricants is provided by synthetic and mineral oils and water emulsions with various additives. However, their use, in most cases, requires waste processing and additional costs for their disposal and also necessitates the use of technologies for cleaning the final products to remove oil contaminants [9,10]. The trends of the last decade in the field of improving the technologies for material processing under pressure are focused on the use of environmentally friendly lubricants or the complete elimination of their use. For example, oil-free lubricants have been developed on a biopolymer basis. They are pre-applied to contact surfaces or fed to the stamping zone using spray systems and drip-feed devices [11]. The disadvantage of consistent (plastic) lubricants is the difficulty of ensuring their delivery and constant presence in the stamping zone. The presence of a viscous lubricating film between the contact surfaces of the tool and the workpiece significantly reduces their adhesion and provides a certain effect in the sheet stamping of aluminum and magnesium alloys when the priority task is to minimize the intensive adhesion of the workpiece to the working surfaces of the punch and die. In the case of sheet stamping of structural carbon steels, when the working surfaces of the stamping tool are subject to both adhesion and abrasive wear, consistent lubricants do not provide the required efficiency. For the specified conditions, it is necessary not only to reduce the intensity of adhesion of the contact surfaces during friction but also to increase the microhardness of the tool's working surfaces [12,13].

Today, one of the most effective approaches to the wear rate reduction of sheet metal stamping tools is the use of solid lubricants in the form of wear-resistant coatings. This approach makes it possible to combine, in a stamping tool, a set of bulk properties of tool steel (high strength and crack resistance) and surface properties of coatings (high microhardness and lubricating ability) and, in the future, completely eliminate the use of liquid and consistent lubricants in performing cold sheet metal stamping [14–16]. Solid lubricant coatings used in stamping are based on ceramic compositions such as CrN, TiAlN, TiCN, and diamond-like carbon (DLC). The absolute leader in providing high lubricating ability is DLC coatings. A few authors have proposed using it to coat micro-punches. The micro-punches made of SKD 11 (analog of the steel under study, X165CrMoV12) for deep drawing of micro-cups made of copper alloy sheets for producing laser diodes were coated with laminated DLC and a Zr/ZrC/NZrC gradient structure 1.2 μm thick via magnetron sputtering [17]. The coating was compared with an uncoated tool and tools with CrN and ZrN coatings. The proposed DLC films exhibit amorphous structures with densely packed nanocrystalline grains with a lower surface roughness (Ra = 4.74 nm). The drawing ratio was improved by 24% compared to other coatings for micro-punches with a diameter of 2.5 mm. Another study [18] was devoted to micro-embossing micro-cavities and micro-grooves into aluminum sheets via CNC coordinate stamping using multi-punches made of SKD11 and AISI420 steel substrates and DLC coatings of 10 to 15 μm. The DLC coating was micro-patterned via maskless lithography. Plasma oxidation partly removed the DLC layers until the 3D array appeared on the steel substrate to form DLC micro-punches. The micro-circular patterns were transformed into micro-pillars in the DLC punch via plasma oxidation. Through CNC micro-embossing, the micro-cavities in the aluminum sheet were produced. Another study [19] demonstrated that using a nano-laminated DLC coating on stamp dies allowed for avoiding delamination and the destruction of the die tool up to 100,000 strokes.

For the deposition of a DLC coating, the most common technologies are magnetron sputtering of graphite targets [20–22] and plasma-assisted chemical deposition from a gas mixture [23,24]. At the same time, DLC coatings have a known limitation, such as a high level of internal stresses, which increases significantly with an increase in the proportion of diamond (sp^3) hybridization in the coating structure and with an increase in the coating thickness. This reduces the adhesion strength of DLC coatings to the tool material and significantly limits the ability of the coating to maintain functional characteristics under significant contact pressures [25,26].

Modern approaches to improving DLC coatings are based on their alloying with various elements (Ti, W, Cr, and Si) and their deposition to thin-film ceramic coatings pre-formed on tool substrates, which reduces residual stresses and improves adhesion to the substrate [27–29]. For example, Abraham et al. [30] studied DLC coatings alloyed with Si. They found that as the alloying element's content increases, the coating's internal stresses decrease significantly, and the adhesion strength improves (however, the coefficient of friction also increases). The authors of the presented study previously found, during a comprehensive analysis of similar DLC:Si coatings, that the best combination of adhesion to the substrate, microhardness, and coefficient of friction at room temperature and under thermal exposure are in coatings containing ~4.0% wt. Si [31]. Experimental studies [32] were conducted on the efficiency of DLC coatings in dry sheet stamping of 304L stainless steel. It was shown that high resistance to burr formation under dry friction and a reduction in stamping forces are provided when TiAlN/DLC coatings are deposited on a stamping tool. The study [33] compares the efficiency of TiAlN, CrN, DLC, and CrN/DLC coatings in dry sheet stamping of X2CrNi1810 corrosion-resistant steel. Tests for the wear resistance and adhesive interaction of the coatings with the counterbody material showed that the CrN/DLC coating reduces adhesion and has the best wear resistance. However, even with a large number of studies conducted to date in the field of improving DLC coatings for sheet stamping, only a small number are concerned with the issues of processing sheet materials made of structural steel. The overwhelming majority of them are limited to the processing of soft materials (mainly aluminum alloys), characterized by relatively low contact pressures on the working surfaces of the tool, and when the main task is to minimize the adhesion of the material under processing to the tool. Therefore, conducting research and obtaining new results in the field of using DLC coatings to improve the efficiency of sheet stamping of workpieces made of structural steels is relevant.

The aim of this work was to study the efficiency of DLC:Si coatings deposited to a pre-formed CrAlSiN ceramic coating to increase the wear resistance of a tool made of X165CrMoV12 die steel during coordinate punching of 4.0 mm thick 41Cr4 carbon structural steel sheets. The coating was deposited using a hybrid unit combining physical vapor deposition and plasma-assisted chemical vapor deposition technologies and investigated using scanning electron microscopy (SEM) (analytically in back-scattered electrons) and energy-dispersive X-Ray spectroscopy (EDX spectra). The adhesion strength of the coatings was determined using scratch testing with a recording of acoustic emissions and the definition of critical forces. The mechanical and physical characteristics were obtained via nanoindentation with a Berkovich pyramid. The tribological characteristics of coatings were assessed using two methods: in the conditions of abrasive action, with a sphere of 20.0 mm in diameter, and under friction–sliding conditions, according to the "ball-on-disk" scheme at room temperature and under heating at 200 °C for two groups of samples in the initial state and after heating in a muffle furnace at 200 °C for 60 min. Full-scale tests of punches with DLC:Si-based coatings were carried out during coordinate punching of 41Cr4 sheet steel.

2. Materials and Methods

2.1. Stamping Tool, Sheet Material Under Processing, and Operational Wear Test Methodology

The studies were conducted using a stamping tool designed for cutting and punching rectangular holes in sheet materials with a 1.0–5.0 mm thickness. The experiments were conducted using steel sheets with a thickness of 4.0 mm, which made it possible to ensure relatively high contact loads on the working surfaces of the tool and to evaluate the efficiency of the coatings under more severe conditions than when stamping thin sheet steel.

The dimensions of the punched rectangular hole were 24.6 × 3.6 mm with a tolerance of ±0.075 mm. The stamping tool under study consists of a movable punch containing a housing and a working part with edges that pressure the material and a fixed die corresponding to the punch profile. Figure 2 shows the design of the stamping tool and the parameters of the working part of the punch.

(**a**) (**b**)

Figure 2. The design of the stamping tool (punch and die) (**a**) and the parameters of the working part of the punch (**b**).

Tool steel X165CrMoV12 was used to produce the stamping tool. The chemical composition of steel X165CrMoV12 and its main physical and mechanical properties are presented in Tables 1 and 2.

Table 1. Chemical composition of tool die steel.

Material	Elements Composition, % Mass									
	Cr	C	Mo	V	W	Si	Mn	P	S	Fe
X165CrMoV12	12.0	1.72	0.68	0.54	0.52	0.36	0.34	0.02	0.01	remain.

Table 2. Physical and mechanical characteristics of tool die steel.

Material	Tensile Strength, MPa	Impact Toughness, J/cm^2	Hardness, HB	Young's Modulus, GPa	Elongation, %	Density, g/cm^3
X165CrMoV12	1900 ± 40	44 ± 5	61 ± 1	206 ± 5	14 ± 1	7.4 ± 0.5

Sheets of carbon structural steel 41Cr4, widely used in industry for manufacturing components of vehicles, electrical devices, and building structures, were used as the workpiece. The chemical composition of steel 41Cr4 and its main physical and mechanical properties are presented in Tables 3 and 4.

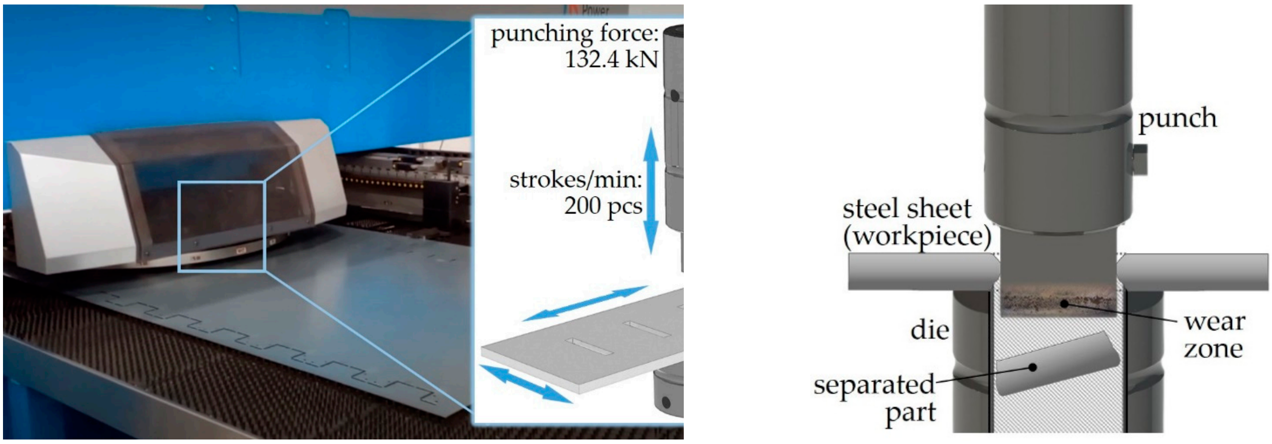
Table 3. Chemical composition of carbon structural steel.

Material	Elements Composition, % Mass							
	C	Cr	Mn	Si	Cu	S	P	Fe
41Cr4	0.42	1.2	0.82	0.36	0.25	0.03	0.02	remain.

Table 4. Physical and mechanical properties of carbon structural steel.

Material	Tensile Strength, MPa	Impact Toughness, J/cm^2	Hardness, HB	Young's Modulus, GPa	Elongation, %	Density, g/cm^3
41Cr4	890 ± 30	40 ± 4	228 ± 3	195 ± 4	10 ± 1	7.6 ± 0.8

The punch tool tests were performed on a PRIMA POWER E5X CNC coordinate punching press (Prima Industrie S.p.A., Collegno, Italy). Figure 3 shows the strategy and scheme for testing the punch tool during coordinate punching of holes in sheet material. The steel sheet is moved along two coordinate axes, and the punch strikes the workpiece at a speed of 200 strokes/min with a force of 132 kN. The gap between the punch and the die was taken as 5% of the thickness of the sheet material under processing and was 0.2 mm on each side.



(**a**) (**b**)

Figure 3. Testing strategy of stamping tool during the processing of sheet material on coordinate punching press (**a**) and scheme of punching rectangular holes (**b**).

Considering that the wear rate of the punch working edges is higher than the wear rate of the die working frame, the wear of the stamping tool was assessed only for the punch. Thus, the punch (the movable part of the stamp) is our research object, since the punch is subjected to more intensive wear and requires more frequent replacement than the fixed die of the stamping mold. The wear analysis was performed on the lateral surfaces of the punches (Figure 3), since preliminary experiments revealed that the prevailing wear center is located on the lateral surface in stamping structural steel and leads to the loss of the working condition of the tool (the wear rate of the end surface is ~2 times less). The study of wear centers was performed using profilograms of the lateral surfaces of the punches obtained by scanning the surface with the highly sensitive contact stylus of the Dektak XT system (Bruker AXS, Billerica, MA, USA). In addition, wear centers were studied in an Axio Lab, an A1 optical microscope (Carl Zeiss MicroImaging GmbH, Jena, Germany). The wear centers were monitored every 10,000 strokes to compare the wear resistance of punches with different surface layer conditions (without and with coatings). The total number of strokes during testing was 50,000. The arithmetic mean values to plot dependencies of wear changes on the number of strokes were calculated based on these data.

2.2. Coating Technology for Stamping Tools

The CrAlSiN ceramic coating was deposited using the physical vapor deposition process (PVD), which is based on the evaporation of the cathode material by moving spots of a vacuum arc of a high-current and low-voltage vacuum arc discharge held by a magnetic field and the deposition of coatings on the substrates from the generated ion flow [34]. The plasma-assisted chemical vapor deposition (PACVD) process is based on a chemical reaction and the decomposition of the gas mixture components under conditions of plasma-assisted glow discharge [35]. It was used to deposit DLC:Si coatings. The results of the X-Ray photoelectron spectroscopy analysis of chemical bonds on the coating surface are published in [36]. The validation via Raman spectroscopy to complete identification and characterization of the compounds are published in [37]. Figure 4 shows the diagram of the process setup unit for CrAlSiN and DLC:Si coating deposition on tribological test samples and stamping tools (the setup is based on the π311 installation, Platit AG, Selzach, Switzerland) [35]. The setup causes the generation of vacuum arc and glow discharge plasma and has a four-channel gas inlet system and two cylindrical cathodes (Cr and Al-Si), which allows for the sequential deposition of CrAlSiN and DLC:Si coatings. The structure formed during vacuum arc deposition of the CrAlSiN coating is a nanocomposite coating with a shell of amorphous nitride Si_3N_4 around crystallites of Cr and Al nitrides [38]. During the deposition of the DLC coating, a layer is deposited due to the chemical reaction between $Si(CH_3)_4$ and C_2H_2 in the gas mixture, occurring near the surface of the substrates. The structure of this layer contains atoms of carbon, hydrogen, and silicon [39]. Table 5 shows the modes of the PVD process for the CrAlSiN coating deposition and the PACVD process for the DLC:Si coating deposition on samples made of die steel.

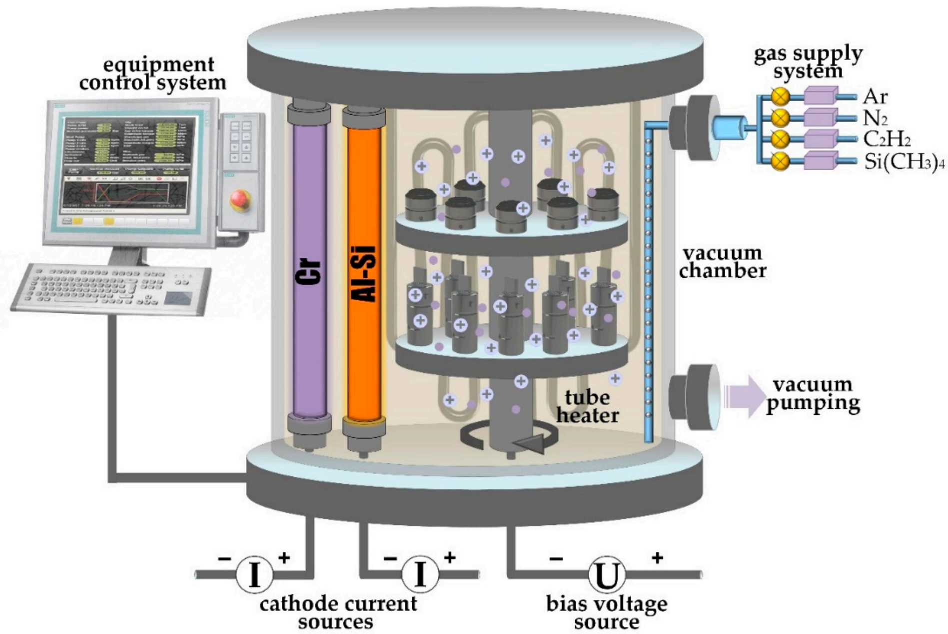


Figure 4. Diagram of the processing unit for the deposition of CrAlSiN and DLC:Si coatings on tribological test samples and stamping tools.

Table 5. PVD and PACVD process modes for the deposition of CrAlSiN and DLC:Si coatings on die steel samples.

Stage of the Process	Coating Deposition Modes						
	Gas Pressure, Pa	Gas Composition, vol.%	Temperature, °C	Bias Voltage, V	Cathode Composition	Arc Current at Cathode, A	Time, min
Heating the vacuum chamber with heaters	0.03	-	480	-	-	-	60
Gas ion cleaning	1.2	100 (Ar)	480	650	-	-	20
Metal ion cleaning	2.2	100 (Ar)	480	800	Al-Si	90	20
CrAlSiN coating condensation	0.9	90 (N_2) 10 (Ar)	480	100	Cr, Al-Si	80 (Cr) 90 (Al-Si)	60
Formation of a transition layer	2.2	16 ($Si(CH_3)_4$) 6 (Ar) 78 (N_2)	480	800	Al-Si	90	5
DLC:Si coating condensation	1.5	4 ($Si(CH_3)_4$) 51 (Ar) 45 (C_2H_2)	180	500	-	-	110

The nanohardness and elastic modulus of the coatings deposited on the die steel samples were tested using a Nano Hardness Tester (CSM Instruments SA, Peseux, Switzerland) with a Berkovich diamond indenter at a load of 4.0 mN. Visual analysis of the coated samples was performed using a Vega 3 scanning electron microscope (Tescan Brno s.r.o., Brno, The Czech Republic). The adhesion level of the coatings to the die steel samples was assessed using a Nanovea M1 scratch tester (NANOVEA Inc., Irvine, CA, USA) via multiple passes of a Rockwell diamond indenter over the surface under study at a linearly increasing load from 1 to 40 N.

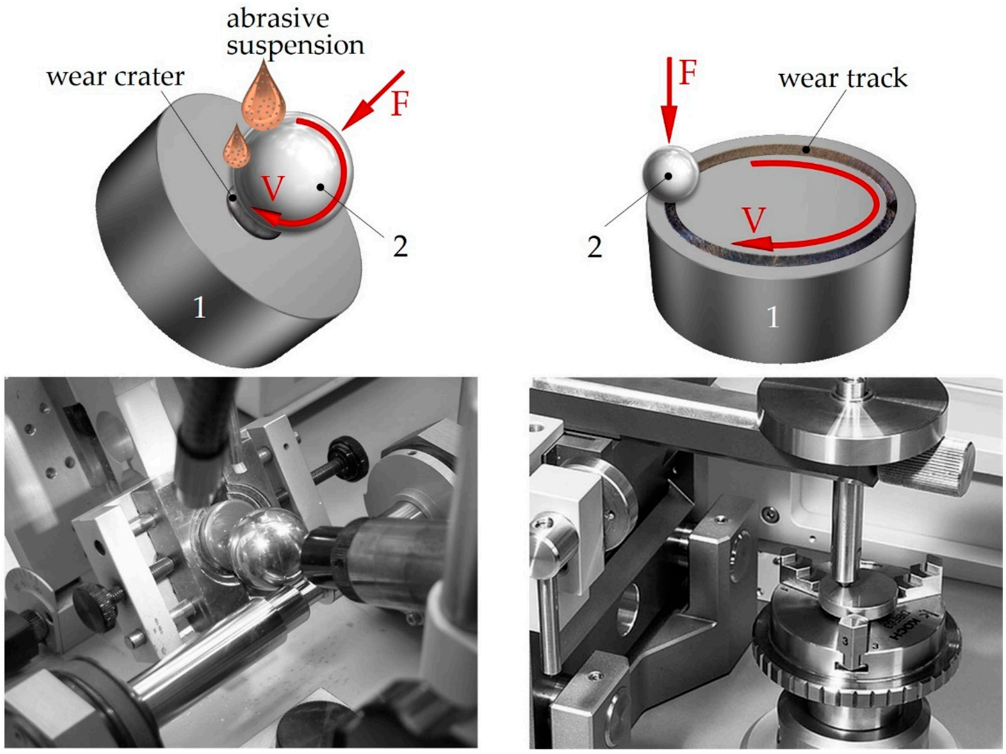
2.3. Methods of Tribological Tests for Wear Resistance

Experimental samples of a disk shape with a diameter of 20.0 mm and a height of 8.0 mm were made from X165CrMoV12 tool steel to conduct tribological wear resistance tests. Three groups of samples were subjected to tribological tests: without coating (1), with CrAlSiN/DLC:Si coating (2), and with CrAlSiN coating (3). A single-layer nanocomposite ceramic CrAlSiN coating was considered as a basic option in tribological tests, characterized by various authors as a coating with excellent abrasion resistance during contact interaction with carbon steels at low and high temperatures [40,41].

The wear resistance of the samples made of tool die (or mold) steel was assessed using two methods (Figure 5):

- Under abrasive action;
- Under the condition of friction–sliding according to the "ball-on-disk" scheme at room temperature and during heating up to 200 °C.

In the first case, the wear intensity of the surface layer of the experimental samples was assessed under abrasive action using the Calowear system (CSM Instruments). A counterbody in the form of a sphere with a diameter of 20.0 mm made of 100Cr6 structural hardened steel rotating at a speed of 59.5 m/min acted on the sample, fixed in a vice, with a force of 0.5 N. At the same time, diamond paste was supplied to the contact zone of the die steel and the steel counterbody. The surface of the die steel sample wore out, and the wear center had the form of a crater. Every 5 min, the wear crater was scanned with the contact stylus of the Dektak XT profilometer and visually analyzed using an Axio Lab.A1 optical microscope. The total test time was 20 min. As a result, data were obtained on the intensity of sample wear at different moments, and the dependencies of the wear crater volume on the test time were drawn. In the second case, the intensity of wear of the surface layer of the experimental samples was estimated during friction–sliding according to the "ball-on-disk" scheme using the TNT-S-AX0000 system (Anton Paar GmbH, Graz, Austria). The tests were carried out with the rotation of the die steel disks relative to the fixed counterbody in the form of a ball made of 100Cr6 structural hardened steel with a diameter of 6.0 mm under a load of 10.0 N and a sliding speed of 12 m/min. The surface of the die steel sample was worn, and the wear center had the form of a track. The coefficient of friction in the contact zone and the profiles of the tracks formed on the experimental samples were studied via scanning on a Dektak XT profilometer and visual analysis on a Vega 3 scanning electron microscope. The friction–sliding tests were carried out at room temperature and under heating conditions up to 200 °C to assess the potential of using DLC:Si coatings under thermal exposure. When studying the behavior of the surface layer of the experimental samples under abrasive conditions, two groups of samples were used: in the initial state and after preliminary heating in a muffle furnace at 200 °C for 60 min.



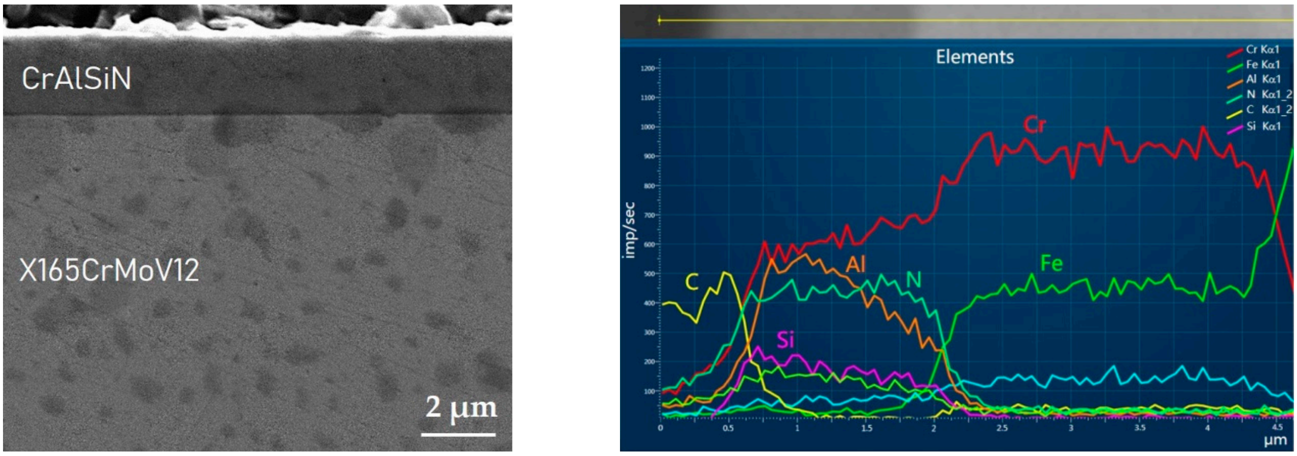
(**a**) (**b**)

Figure 5. Diagrams and general views of working zones of devices for tribological testing of experimental samples under conditions of abrasive wear (**a**) and friction–sliding (**b**): 1—samples made of tool steel X165CrMoV12; 2—samples of counterbodies made of structural steel 100Cr6.

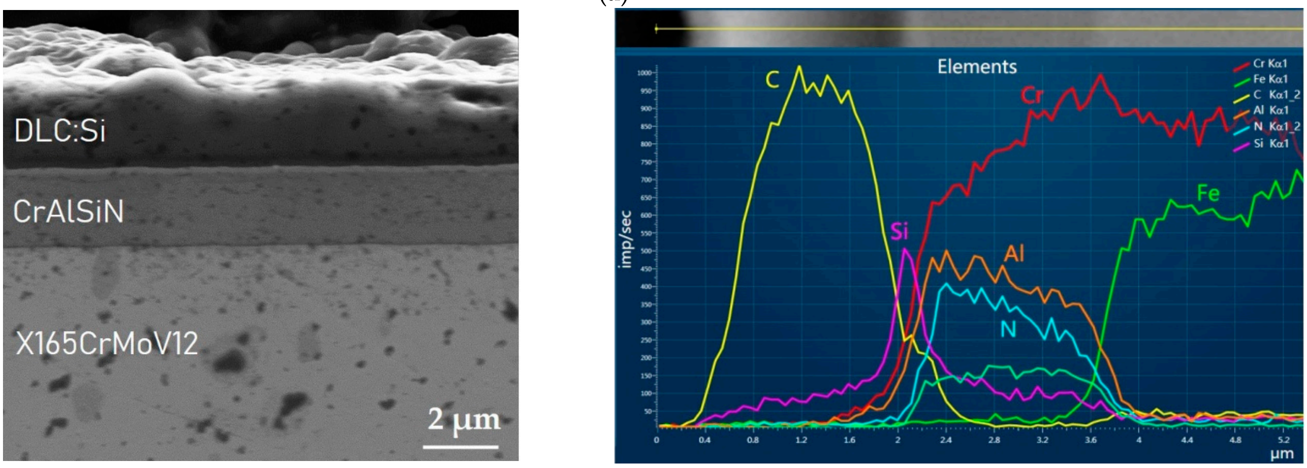
3. Results

3.1. Physical and Mechanical Characteristics of Coatings Deposited on Die Steel

Figure 6 shows SEM images of cross-sections of the CrAlSiN and CrAlSiN/DLC:Si coatings deposited on X165CrMoV12 die steel samples and EDX spectra of the distribution of elements in the surface layers of the coated samples. As can be seen in Table 6, under the deposition modes selected in the study, the thickness of the CrAlSiN monocoating was 2.1 ± 0.15 µm, and the total thickness of the CrAlSiN/DLC:Si coating was 4.0 ± 0.3 µm, where CrAlSiN was 1.9 ± 0.1 µm and DLC:Si was 2.1 ± 0.2 µm. The carbon content on the surface of the CrAlSiN coating (up to 0.5 µm on the linear *X*-axis in Figure 6a) corresponds to the residual epoxy resin and normal atmospheric contamination. It is seen that the outer DLC layer contains silicon in addition to the carbon component (Figure 6b). The concentration of Si increases significantly in the transition layer and then decreases slightly along the depth of the CrAlSiN nitride layer. This transition layer was deposited in a 16% ($Si(CH_3)_4$) + 6% (Ar) + 78% (N_2) gas mixture using an Al-Si cathode (Table 5). The composition of the gas mixture and cathode explains the presence of Si. Such a coating composition ensures satisfactory adhesion strength of DLC:Si coatings, comparable to traditional nitride coatings such as CrAlSiN.



(**a**)



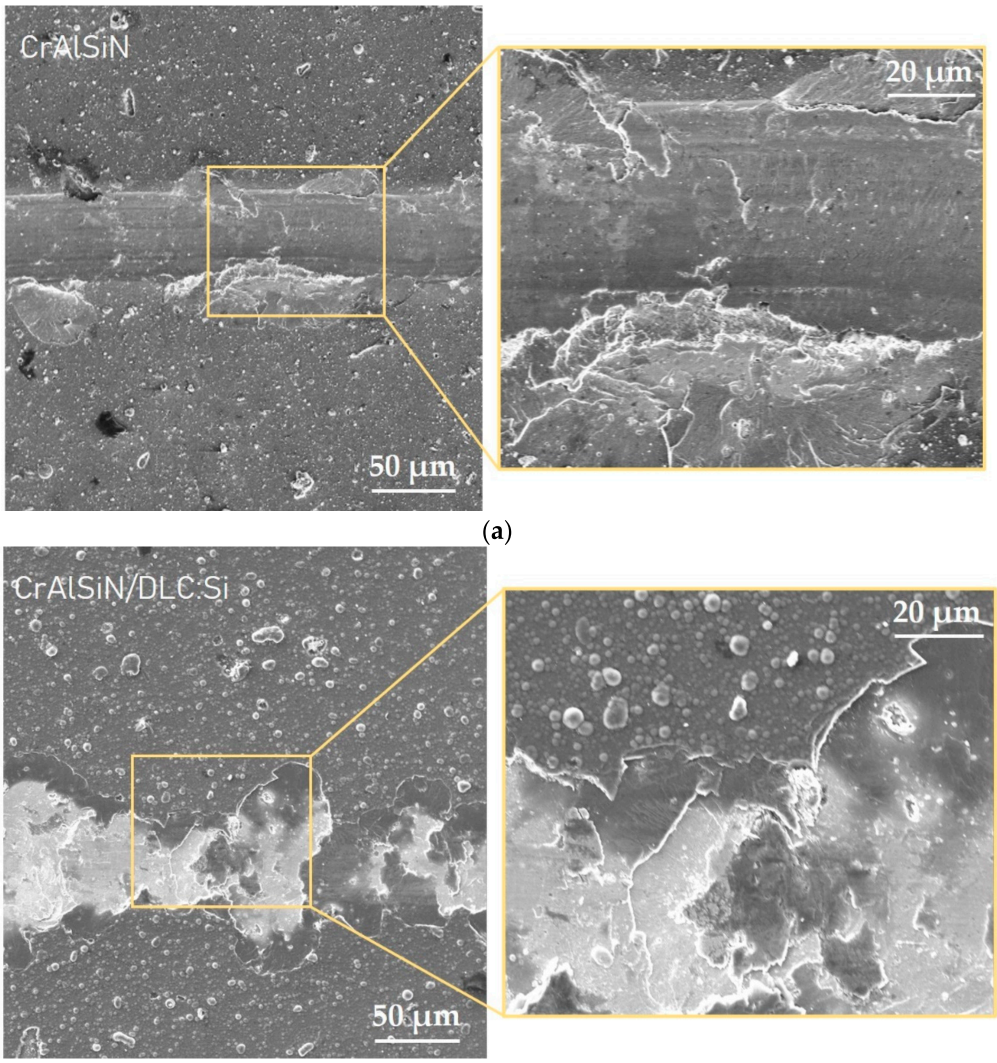
(**b**)

Figure 6. SEM images (**left**) of cross-sections of die steel specimens with CrAlSiN (**a**) and CrAlSiN/DLC:Si (**b**) coatings and EDX spectra (**right**) of element distribution in the surface layers of the coated specimens.

Table 6. Physical and mechanical characteristics of samples made of X165CrMoV12 die steel with two coating options.

Coating Option	Coating Thickness, µm	Adhesive Strength of the Coating, N		Penetration Depth at a Load of 4 mN, nm	Nanohardness, GPa	Elasticity Modulus, GPa
		F_1	F_2			
CrAlSiN	2.1 ± 0.15	13 ± 2	29 ± 1	228 ± 8	29 ± 2	308 ± 6
CrAlSiN/ DLC:Si	1.9 ± 0.1/ 2.1 ± 0.2	14 ± 2	27 ± 2	264 ± 12	22 ± 2	221 ± 8

The assessment of the adhesion strength of the coatings via scratch testing with a recording of critical forces, where F_1 is the onset of coating failure with the crack formation and F_2 is the detachment of local areas from the substrate, shows that CrAlSiN and CrAlSiN/DLC:Si coatings have very close values: F_1 was 13 N and 14 N, and F_2 was 29 N and 27 N, respectively (Table 6). Critical forces F_1 and F_2 are identified by peaks in the amplitude of the acoustic emission signal that occur with a sharp change in the depth of indenter penetration due to its entry into a crack or a peeled-off section of the coating. At the same time, the nature of the destruction of the CrAlSiN and CrAlSiN/DLC:Si coatings deposited to the die steel is different, as can be concluded by the SEM images of the tracks formed during scratch testing (Figure 7). If the nitride coating exhibits adhesive detachments of coating sections mainly localized along the edges of the scratch, then the diamond-like coating is characterized by mixed adhesive–cohesive and interlayer detachment of the coating. Table 6 also presents the experimental data on the physical and mechanical characteristics of the CrAlSiN and CrAlSiN/DLC:Si coatings obtained via nanoindentation. As follows from the data, as the depth of indenter penetration increases, the hardness of the surface layer decreases. Within the load (4.0 mN), the nanohardness of the coated samples is 29 ± 2 GPa and 22 ± 2 GPa, respectively. The two coatings under study differ significantly in their elastic moduli, in particular, 308 GPa for the CrAlSiN coating and 221 GPa for the CrAlSiN/DLC:Si coating.



(a)

(b)

Figure 7. SEM images of the fracture behaviors during scratch testing of CrAlSiN (**a**) and CrAlSiN/DLC:Si (**b**) coatings deposited on die steel samples.

3.2. Tribological Characteristics of Coatings Deposited on Die Steel

Figure 8 shows the experimental dependencies of the volumetric wear of X165CrMoV12 die steel samples without coatings and with CrAlSiN and CrAlSiN/DLC:Si coatings on the time of abrasive action and the wear well profiles formed after 20 min of testing in contact with 100Cr6 steel. It is clearly seen that the uncoated tool material demonstrates intense abrasion with the formation of large-volume wear wells with a depth of ~8.9 μm. The deposition of CrAlSiN coatings makes it possible to reduce the volume of abrasive wear by 5 times (the well depth is reduced to 4.8 μm), and CrAlSiN/DLC:Si coatings demonstrate maximum efficiency, reducing the volumetric wear of die steel by up to 15 times (the well depth is reduced to 2.2 μm). An increase in resistance to abrasive wear is also observed for the coated samples that were preheated and held in a muffle furnace at a temperature of 200 °C (dotted lines in Figure 8). At this level of thermal exposure, tempering and a decrease in the hardness of the surface layer of die steel occurs due to the process of martensite decomposition and the release of excess carbon from it [42]. It is explained that the volumetric wear of tool steel after thermal exposure is 2.4 times greater than for the original sample. Using CrAlSiN and CrAlSiN/DLC:Si coatings even after heat treatment ensures a decrease in the volume of abrasive wear by 2.5 and 9 times, respectively.

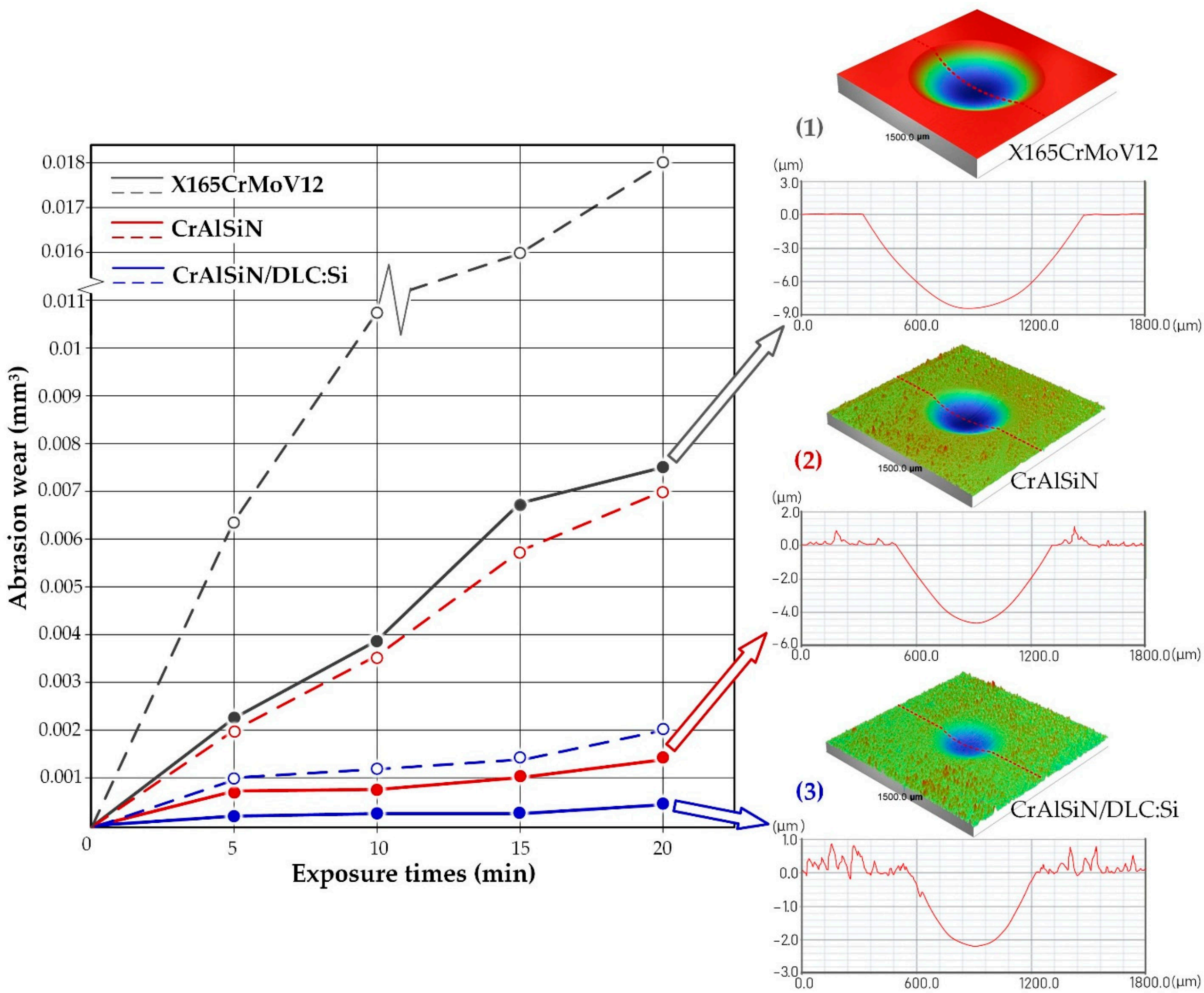
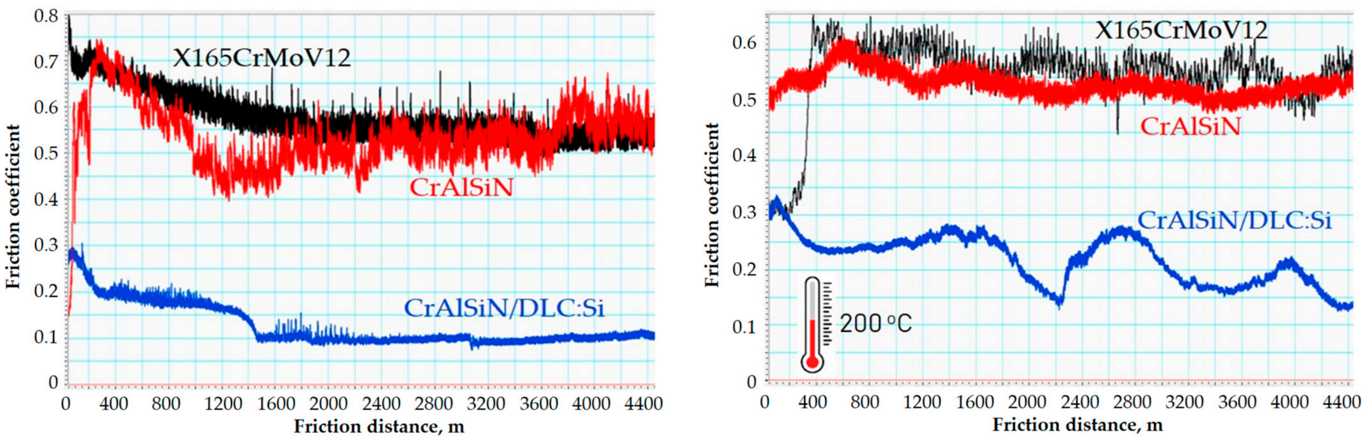


Figure 8. Dependencies of volumetric wear of samples made of die steel without coatings and with CrAlSiN and CrAlSiN/DLC:Si coatings on the time of abrasive action and profiles of wear wells at the end of testing (solid line is for samples in the initial state; dotted line is for samples after holding in a muffle furnace at a temperature of 200 °C).

It is generally accepted that materials with high hardness are more resistant to abrasive wear, since the higher the hardness, the smaller the depth of penetration or crushing under the exposure of particles of the medium and the counterbody [43,44]. However, the results described above show that despite the higher hardness of the CrAlSiN coating compared to the CrAlSiN/DLC:Si coating (Table 6), it is significantly more susceptible to wear throughout the entire testing distance (Figure 8). In other words, the hardness cannot unambiguously characterize the wear resistance of the surface layer of the tool material with a coating.

The results of the tribological tests under sliding friction conditions are more informative. Figure 9 shows the change in the coefficient of friction with an increasing duration of the sliding friction for samples made of die steel without a coating and with CrAlSiN and CrAlSiN/DLC:Si coatings in contact with 100Cr6 steel balls. It is evident that the coefficient of friction curves for samples with the CrAlSiN coating under room temperature test conditions have a large oscillation amplitude throughout the subsequent testing, even after running-in. The average value of the coefficient of friction is 0.45–0.5, which is slightly less than the coefficient of friction of the original samples made of X165CrMoV12 die steel (0.55–0.6). A fundamentally different character is observed for the samples with CrAlSiN/DLC:Si coatings: the coefficient of friction stabilizes after running-in and is about 0.1 throughout the subsequent testing. The low value of the coefficient of friction for the samples with a CrAlSiN/DLC:Si coating indicates that the force required to initiate sliding between the counterbodies is significantly less than the resistance force to the counterbody movement relative to the uncoated and CrAlSiN-coated samples. It indicates that intense adhesion occurs between the uncoated and CrAlSiN-coated samples and the steel counterbody as a result of intermolecular interaction. It is also indicated by the observed significant amplitude of the coefficient of friction curves.



(a) (b)

Figure 9. Change in the coefficient of friction with increasing duration of sliding friction of samples made of die steel without coating and with CrAlSiN and CrAlSiN/DLC:Si coatings in contact with balls made of 100Cr6 steel without heating (**a**) and at a temperature of 200 °C (**b**).

The above-described features of the contact interaction of the surface layer of the X165CrMoV12 tool material with the CrAlSiN and CrAlSiN/DLC:Si coatings are illustrated by the profilograms and SEM images of the wear tracks formed during sliding friction under room temperature conditions (Figure 10). As a result of the contact interaction, a wide wear track (of ~1000 µm) was formed on the uncoated sample. The dimensions of the wear track are significantly smaller on the surface of the CrAlSiN-coated sample, but a substantial volume of counterbody material adherents is observed. The tool material with the CrAlSiN/DLC:Si coating does not have a pronounced wear track, and there are no counterbody material adherents. The presence of a DLC:Si layer with a minimum coefficient of friction in the contact zone effectively protects the surface layer of the die steel from intermolecular interaction with the steel counterbody and the associated wear.

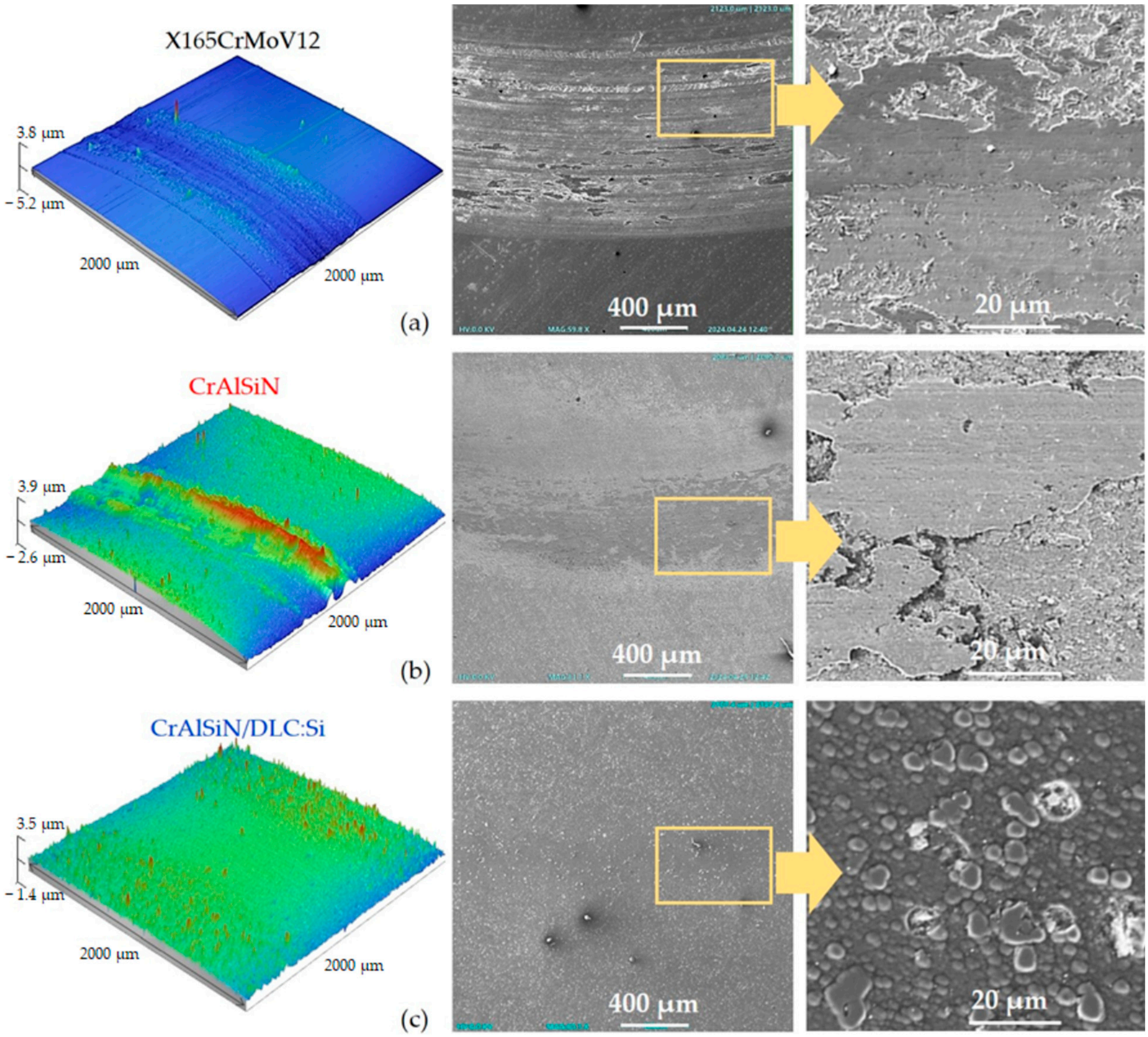


Figure 10. Profilograms (**left**) and SEM images (**right**) of wear tracks formed during sliding friction of different die steel samples in contact with 100Cr6 steel balls with no heating: without coating (**a**), with CrAlSiN coating (**b**), and with CrAlSiN/DLC:Si coating (**c**).

Figures 9 and 11 show the results of similar studies with sliding friction, but they were conducted under conditions of heating the samples in the tribometer chamber. A comparison of the experimental results obtained at room temperature and under thermal exposure at 200 °C allows us to conclude as follows: If the thermal action did not significantly affect the change in the coefficient of friction for the initial material X165CrMoV12 and the sample with the CrAlSiN coating, then the nature of the frictional interaction changed significantly for the samples with the CrAlSiN/DLC:Si coating. It is evident (Figure 9) that the change in the coefficient of friction over the test distance is non-monotonic, with values of 0.15–0.25. It can be assumed that this reflects the processes of periodic adhesion of the CrAlSiN/DLC:Si coating to the steel counterbody, caused by the transformation occurring in the structure of the DLC:Si layer under thermal action when some proportion of diamond (sp^3) hybridization is transformed into graphite (sp^2) [45,46]. However, even with the identified slight decrease in the antifriction characteristics of the CrAlSiN/DLC:Si coating, its wear resistance under friction–sliding under thermal action significantly exceeds the characteristics of samples without a coating and with a CrAlSiN coating. The above is clearly illustrated by the profilograms and SEM images of wear tracks formed during sliding friction under heating conditions, as shown in Figure 11. As a result of contact interaction, wear tracks of significant width (more than 1000 μm) with pronounced longitudinal grooves are formed on the samples without coating and with CrAlSiN coating, and adhesions of the counterbody material are present on the surface. The wear track formed on the sample with CrAlSiN/DLC:Si coating has a width of no more than 400 μm, and adhesions of the counterbody material are absent. Thus, the presence of an antifriction layer of DLC:Si between the contacting surfaces, even under thermal exposure, allows for minimizing the wear of the die steel. The described results allow us to conclude about the prospects of DLC coatings for protecting forming tools intended for processing non-ferrous metals and steel blanks that have not yet been fully realized.

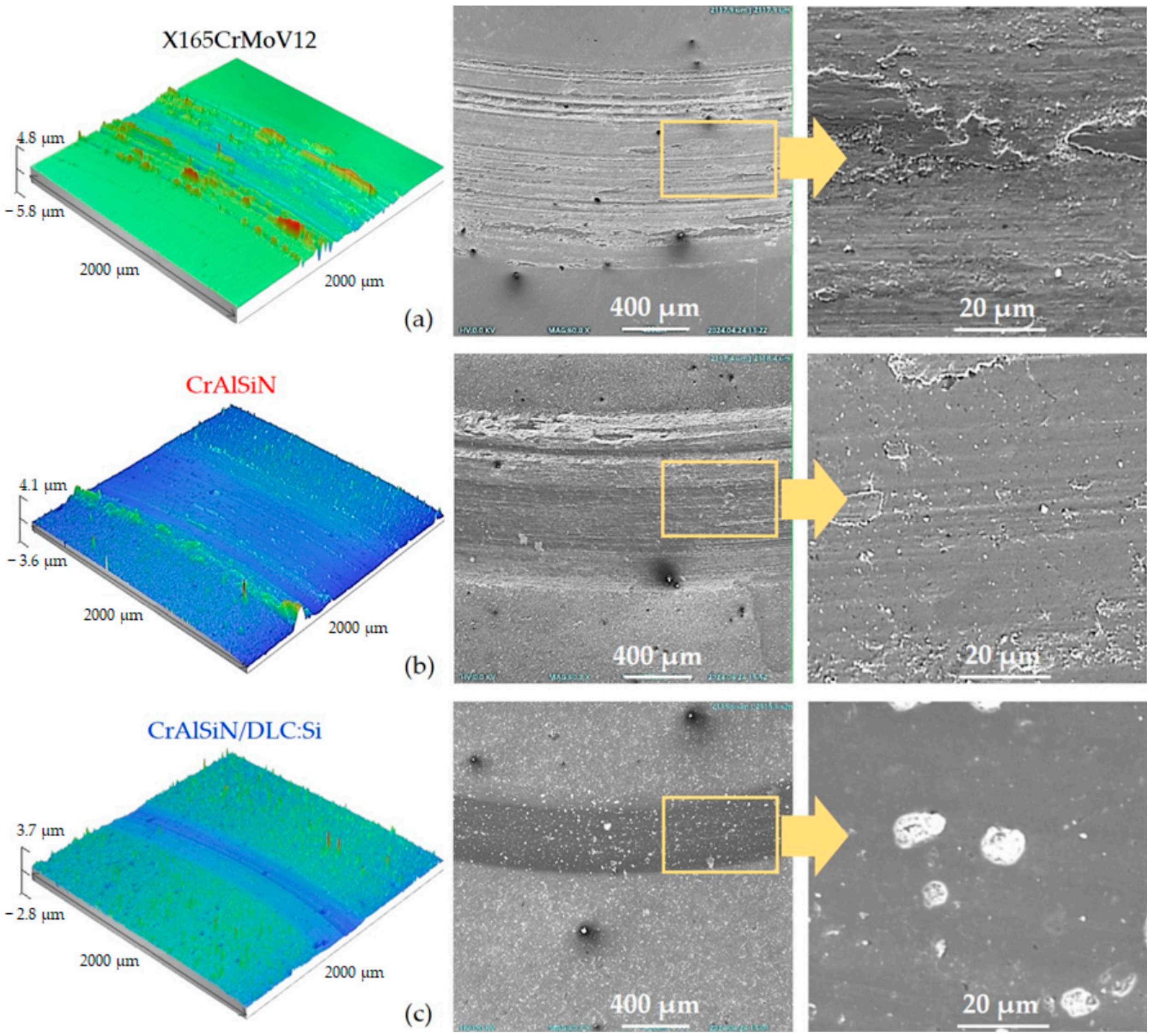
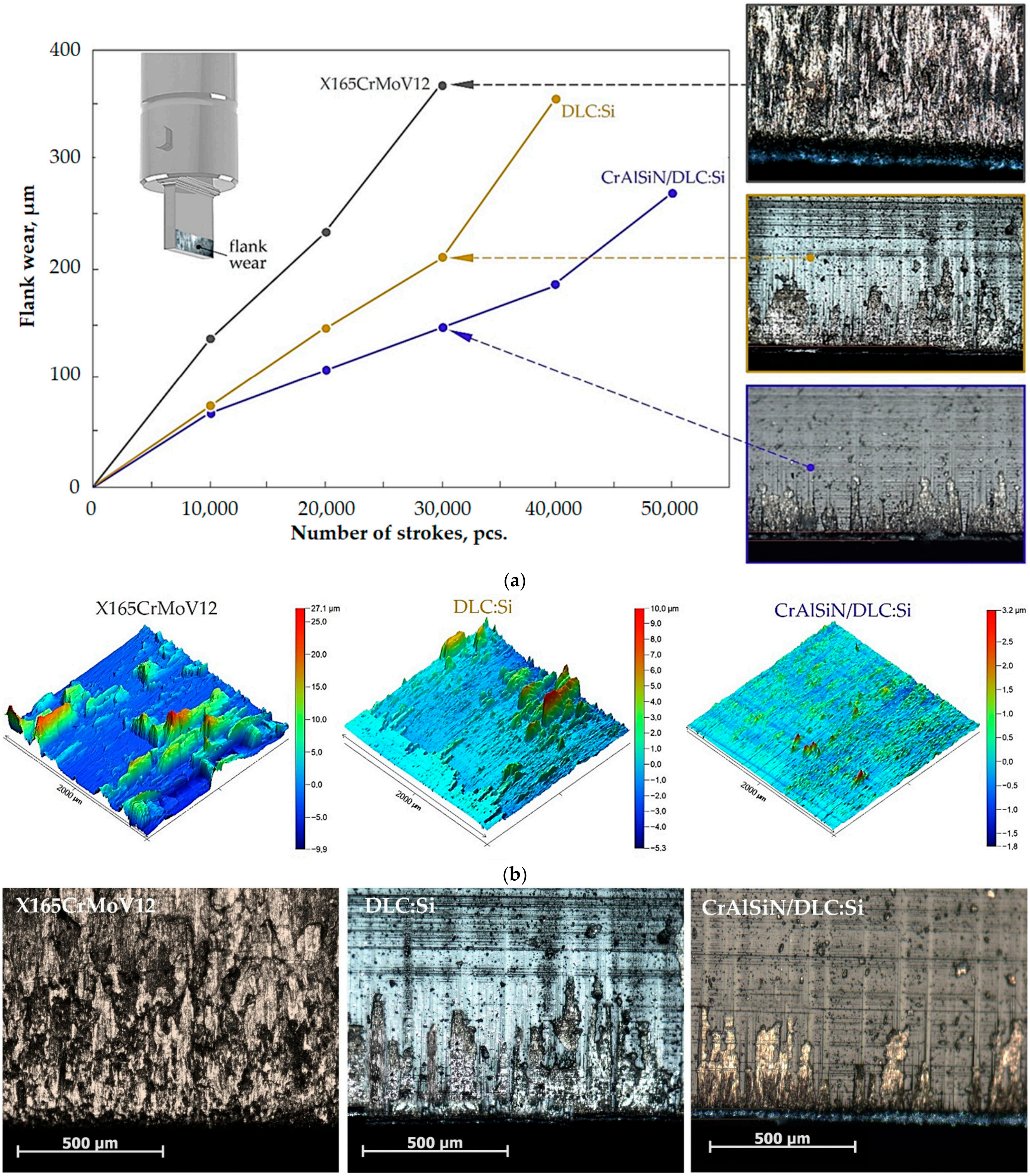


Figure 11. Profilograms (**left**) and SEM images (**right**) of wear tracks formed during sliding friction of different die steel samples in contact with 100Cr6 steel balls with heating at 200 °C: without coating (**a**), with CrAlSiN coating (**b**), and with CrAlSiN/DLC:Si coating (**c**).

3.3. Wear Resistance of Die Tools with Coatings During Punching of Sheet Steel

At the final stage of the research, full-scale tests of punches with DLC:Si-based coatings were carried out during coordinate punching of 41Cr4 sheet steel. Based on the results of previous tribological studies and the low contribution demonstrated by CrAlSiN monocoatings to reducing frictional interaction with the counterbody and the wear intensity of the die steel, this coating was not used in durability tests of a real die tool. Three versions of punches made of X165CrMoV12 steel were tested: without any coating, with the CrAlSiN/DLC:Si coating (as having proven itself well in tribological tests), and with DLC:Si monocoating (to identify the contribution of CrAlSiN as an intermediate layer). Figure 12 shows the experimental dependencies of wear on the lateral surface of punches made of X165CrMoV12 die steel with different coatings on the number of strokes when punching through rectangular holes in sheet material made of 41Cr4 steel, as well as profilograms of the working lateral surfaces of punches after 30,000 strokes. The kinetics of wear development for the three samples under study have a classical character for forming processes, and this includes running-in, steady-state, and accelerated wear stages, but the wear rates differ significantly. The wear rate of X165CrMoV12 samples without a coating is already quite high at the running-in stage and does not decrease further, which can be associated with the insufficient hardness of the surface layer and intense adhesion to the workpiece material, as evidenced by the profilogram of the lateral surface of the punch, on which numerous adherences are visible. The use of the DLC:Si coating significantly slows down the wear development at the running-in stage, but subsequently, the wear rate increases due to changes in friction conditions caused by coating breakthroughs, which leads to adhesive seizure and accelerated wear (the optical image of the wear wells and the profilogram of the lateral surface illustrate the above-described features). The punches with CrAlSiN/DLC:Si coatings are characterized by a slowdown in wear at the running-in stage and the longest stage of steady wear, which is ensured by the high adhesive strength of the coating and the minimum coefficient of friction, reducing adhesive seizure in the contact zone with the workpiece, which is confirmed by the optical image and the profilogram of the wear lateral surface. It should be noted that the morphology of punches with a DLC:Si outer layer corresponds to the typical DLC-type coatings deposited using the PVD method. However, all these irregularities are smoothed out after the first strokes during the punch running-in, and as can be seen, the coating fulfills its functional purpose. If we take the wear value on the lateral surface of 250 μm as critical wear, then the wear resistance of punches without a coating is 21,000 strokes, is 33,000 strokes with a DLC:Si coating, and 48,000 strokes for a CrAlSiN/DLC:Si coating. Thus, the conducted full-scale tests allow us to consider the deposition of CrAlSiN/DLC:Si coatings as an effective approach to increasing the wear resistance of stamping tools when solving a wide range of technological problems of sheet stamping of structural steels.



(a) (b) (c)

Figure 12. Kinetics of wear development on the lateral surface of punches made of X165CrMoV12 die steel with an increase in the number of strokes when punching through rectangular holes in sheet material made of 41Cr4 steel (**a**); profilograms of the working lateral surfaces of punches after 30,000 strokes (**b**); optical images of wear wells after 50,000 impact strokes (**c**).

3.4. Comparison of the Obtained Results with Similar Studies

Table 7 provides a comparison of the results obtained with those of the previously published works. As can be seen, the studies in improving the wear resistance of punching tools have no systematic character, and previously, the attention of the authors was more addressed to the relatively soft, non-ferrous sheet materials that trend to the adhesion and "build-ups" on the tool such as copper, aluminum, and tin coatings. In the results of a study that are the closest analog [19], the performance in 48,000 strokes for coordinate punching of 41Cr4 steel sheet corresponds the promising results compared to 100,000 strokes for aluminum alloy sheets using a DLC-nanolaminated tool made of similar material (SKD 11).

Table 7. Comparison of performance parameters in punching using a coated tool.

Coating Composition	Coating Thickness	Deposition Method	Material of Punch Substrate	Technology	Sheet Material	Performance	Reference
Double-layer CrAlSiN/DLC:Si	1.9/2.1 µm	PACVD/PVD	X165CrMoV12	Coordinate punching	41Cr4 steel	48,000 strokes	Current study
Laminated DLC with Zr/ZrC/NZrC gradient	1.2 µm	PVD	SKD 11 (analog of X165CrMoV12)	Deep drawing of micro-cups	Copper	Improved in drawing ratio by 24%	[17]
DLC (micro-patterned)	10–15 µm	PVD + maskless lithography (plasma oxidation)	SKD11 and AISI420 steel	Coordinate micro-embossing	Aluminum	Not provided	[18]
DLC (nanolaminated)	10 nm	PVD (nanolamination)	SKD 11	Micro-stamping	Aluminum	100,000 strokes	[19]
TiN and Cr	Not provided	PACVD	Not provided	Strip drawing	Aluminum (1050A)	Not provided	[47]
B_4C and Mo	5 µm	PVD	Not provided	Drawing	Tin coated thin steel	Mo coating exhibits better wear resistant properties	[48]

4. Conclusions

(1) The use of the combined physical vapor deposition and plasma-assisted chemical vapor deposition technologies allows for the deposition of wear-resistant CrAlSiN/DLC:Si coatings with high adhesive strength similar to that of traditional nitride coatings on the surfaces of tools made of semi-heat-resistant die steels of the X165CrMoV12 type. The formed CrAlSiN/DLC:Si coatings are characterized by a mixed adhesive–cohesive and interlayer failure mechanism.

(2) The CrAlSiN/DLC:Si coatings allow for a 15-fold and 3-fold reduction in the wear well volume compared to samples without coatings and samples with CrAlSiN coatings under conditions of abrasive action on X165CrMoV12 samples in contact with 100Cr6 steel. CrAlSiN/DLC:Si coatings are effective in increasing wear resistance and reducing the volume of the wear wells by 9 and 3.6 times compared to the die steel without coatings and with CrAlSiN coatings even after preliminary thermal action, causing the loss of hardness of the surface. These data indicate that the hardness of the coating does not characterize its resistance to abrasive wear.

(3) The most informative tests are under friction–sliding conditions in contact with 100Cr6 structural steel. At room temperature, the CrAlSiN/DLC:Si coatings allow for reducing the coefficient of friction from 0.45–0.5 to 0.1 compared to samples without

coatings and from 0.55–0.6 to 0.1 for the samples with CrAlSiN coatings due to the reduction of intermolecular interaction and adhesion, which minimizes wear and eliminates sticking. At thermal exposure, the coefficient of friction increases slightly to 0.15–0.25 due to the structural transformation of the DLC:Si layer, but the coating effectively protects the surface of the die steel from intermolecular interaction and wear. The wear track width of the samples with CrAlSiN/DLC:Si coatings decreases by 2.5 times compared to the samples without coatings and with CrAlSiN coatings. The build-ups are absent.

(4) The results of full-scale tests of punches made of X165CrMoV12 die steel with DLC:Si-based coatings during coordinate punching of 41Cr4 sheet steel with a thickness of 4.0 mm showed that the CrAlSiN/DLC:Si coating ensures a minimum wear rate of the tool's working surfaces at all stages of wear development, while DLC:Si monocoatings significantly reduce the wear intensity only at the running-in stage. Thus, the wear resistance of punches was increased by 2.2 times for the tool with CrAlSiN/DLC:Si coatings and by 1.5 times for the tool with DLC:Si nanocoatings when estimated by the amount of wear on the tool's lateral surface,

(5) The set of studies allows us to consider the deposition of CrAlSiN/DLC:Si coatings as a promising approach to increasing the wear resistance of stamping tools when solving a wide range of technological problems of sheet stamping of structural steels (including sheet stamping with heating). Although today the main traditional area of use of DLC coatings in sheet stamping processes is the processing of alloys that do not contain iron, they have unrealized prospects for protecting forming tools when processing steel sheet blanks.

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